NASA Technical Memorandum 107224

Potential Starter/Generator Technologies for Future Aerospace Applications

Malik E. Elbuluk
University of Akron
Akron, Ohio

and

M. David Kankam
Lewis Research Center
Cleveland, Ohio

Prepared for the
National Aerospace and Electronics Conference
cosponsored by IEEE, WBAFB, and AESS
Dayton, Ohio, May 20–24, 1996

National Aeronautics and
Space Administration

Potential Starter/Generator Technologies for Future Aerospace Applications

Malik E. Elbuluk
Department of Electrical Engineering
University of Akron
Akron, OH 44325-3904
Tel. (216) 972-6531
Fax. (216) 972-6487
email:melbuluk@uakron.edu

M. David Kankam
Power Technology Division, MS 301-5
NASA Lewis Research Center
Cleveland, OH 44135
Tel. (216) 433-6143
Fax. (216) 433-8311
email: m.kankam@lerc.nasa.gov

Abstract

This paper presents a search and comparative review* of the literature available on variable speed constant frequency (VSCF) technologies. In particular, most of the progress made in the past ten years, using power electronics and electric machines for VSCF systems, is reported. Two VSCF systems, based on induction and switched reluctance machine technologies, are presented . The research on the singly- and doubly-fed induction machines has focused on VSCF for wind power generation, whereas that on switched reluctance machines has been directly studied as a VSCF technology in aircraft system. Results obtained so far favor the switched reluctance machine over the induction machine.

Based on the foregoing comparative review, it is recommended that the induction machine be fully investigated as a VSCF drive for aircraft systems. The findings should then be compared with the counterpart SRM system. Issues of comparison may include fault tolerance and redundancy, power density, torque requirements, overload ratings, temperature range and cooling, efficiency and stability over expected operating speed range.

1. Introduction

The advancement in power electronics and electric drives is expected to enhance the reliability, fault tolerance, power density and performance of the concept of the more electric aircraft (MEA). The starter/generator is a key technology in the MEA [1] for providing engine start and power to electric driven pumps and other electrical loads and actuators.

Traditionally, electric power for aerospace applications has been generated over many years, using the wound-field synchronous machine to obtain constant frequency of 400 Hz. This machine/drive system is known as a constant speed drive (CSD) [2]. The quality of ac waveforms and control of the machine have been improved considerably. However, the machine has been challenged by different requirements associated with various power types, increased reliability, ease of maintenance, cost, higher operating speeds and temperatures. Operating experience has shown that variable-speed constant frequency (VSCF) operation has resulted in promising technologies that overcome the above limitations, and provide better starter/generator schemes for aerospace applications. VSCF-based aircraft power systems have significantly longer mean time between failures, and contribute to quicker mission turn around times compared to the CSD-based power systems that are prevalent on existing aircraft. Thus, if VSCF-based aircraft electric power systems were developed to fit into the existing envelope of present CSD-based electric power systems, the benefits of increased reliability, lower recurring costs and shorter mission cycle times could be brought to existing aircraft that employ CSDs [35].

Figure 1 shows a block diagram of a typical VSCF system. In the motoring mode, the constant frequency system provides power, through the interface power converter, to the electric machine which acts as a starter to a load such as an aircraft engine. In the generating mode, the variable speed prime mover, such as gas turbines in aircraft or vertical and horizontal wind turbines, provides power to the electric machine which generates variable frequency power that delivers power via the interface converter to the constant frequency system. Depending on the control strategy signals may be fed from all, or some of the VSCF components, to the control system which provides the gating signals to the interface converter.

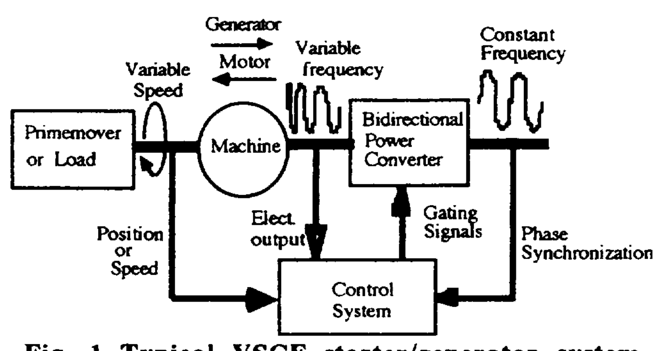


Fig. 1 Typical VSCF starter/generator system

2. Objectives and Contributions of This Paper

This paper presents a search of the literature available on VSCF technologies. In particular, the paper describes most of the progress made in the past ten years, on the use of power electronics and electric machines for VSCF systems. The research has focused on two VSCF

* This work was supported during 1995 summer Faculty Research Fellowship from The Power Technology Division at NASA Lewis Research Center.

technologies that have the potential in aerospace applications. The first technology is based on either the singly-fed induction machine or the doubly-fed machines (typified by the brushless reluctance machine). The second technology uses the switched-reluctance machine (SRM).

The practical advantages of the simple construction and lower cost of induction machines, compared to synchronous machines, have resulted in a widespread use of the squirrel-cage induction machine as a generator in the utility power system which uses wind or hydro power [2]-[7]. However, many considerations influence the design and protection of an induction machine when used in a generator plant [3]. To minimize the impact of an induction generator on a power system, a utility may require the plant to be operated at 95% or more power factor [3]. To meet this requirement, capacitors need to be installed to supply most of the excitation requirements for the induction generator. Placement of capacitors, however, becomes very critical in preventing over-voltage problems due to self-excitation [7].

The operation of a squirrel cage induction machine as an isolated starter/generator unit, for aerospace applications, has been studied by The University of Wisconsin at Madison, with financial support from NASA Lewis Research Center [8]-[12]. The use of power electronics resulted in a more advanced system that eliminated many of those problems associated with induction generators used in connection with utility power systems. For example, some advantages of the system were that no capacitors were required for excitation, and the system operated at unity power factor. The Wisconsin system was based on field-oriented-controlled squirrel-cage induction machines, interconnected via a 20 kHz high frequency (HF) resonant ac link. The research demonstrated the theoretical and experimental results of a 10 hp system. Further research on this technology requires building on the reported work to investigate the use of a squirrel-cage induction motor in an aircraft environment, to assess its advantages and limitations as a starter/generator in aerospace applications.

The doubly-excited machine uses the slip power recovery system in a wound-rotor induction machine fed through dual pulse width modulated (PWM) converters. This approach has been investigated independently by Ohio State University on a National Science Foundation (NSF) Grant, and Oregon State University funded by the Electric Power Research Institute (EPRI). Ohio State University used field-oriented current regulation and decoupled active and reactive power to achieve overall control for a 50 hp machine. Experimental verification of the concept was first reported by Oregon State University. Both Universities have developed the concept for wind power generation. The use of the concept as a starter/generator in an aircraft system is yet to be investigated.

The US Air Force has funded work by General Electric (GE), Sundstrand and the University of Kentucky to investigate the use of the switched reluctance machine as a starter/generator. The work done for different power levels up to 250 kW, and under different loading conditions is directly applicable to the aircraft system. The ripple contents on the dc link of the switched-reluctance generator is a drawback of the system. However, with the intensity and speed of the research, it is expected that such problems will be resolved. The simple construction and higher power density of the machine may give it an advantage over the induction machine-based systems.

To-date, there is no comparative study of the three VSCF systems in an aircraft environment. Such research is essential in assessing the suitability of one technology over the others.

3. Induction Machines as Starter/Generator

The research reported on the use of induction machines as a starter/generator has focused in two machine configurations. One uses the conventional three-phase squirrel-cage induction machine, and the other uses the doubly-fed machines which comprise the squirrel-cage and the round-rotor induction machines. Both configurations are described below.

3.1 The Squirrel-Cage Induction Motor

Over the past ten years, a series of research projects at the University of Wisconsin in Madison, have studied the use of a squirrel-cage induction motor as a starter/generator [8]-[14].

The initial power conversion system used a single phase 20 kHz high frequency (HF) resonant link proposed by Sood and Lipo [8-[9]. A low frequency, variable amplitude and frequency three-phase system is synthesized from a zero-voltage switching Pulse Density Modulated (PDM) Converter which offers low distortion. The study focused on the operation and characteristics of the interface converters, outlined the principle of PDM, and demonstrated the attractiveness of HF link for isolation and power density-sensitive aerospace applications. Power system requirements for aircraft secondary power system are among some of the examples. A block diagram of the HF link is shown in Fig. 2. The study, also, investigated interfacing the HF link to an induction motor using a volt-sec or flux (V/f) controller.

A follow-up study by Sul and Lipo [10]-[11] investigated a 1-kW, current-fed, current-regulated indirect Field-Oriented Controller (FOC) for an induction machine operating from the HF 20 kHz resonant ac voltage link. The link voltage buildup and regulation, transient behavior of the ac link, dynamic performance of the FOC, four-quadrant operation of induction motor, unity power factor of the 60 Hz source and power matching are among the issues presented in this work. Fig. 3 shows a block diagram of the field-oriented controlled induction motor from the HF link.

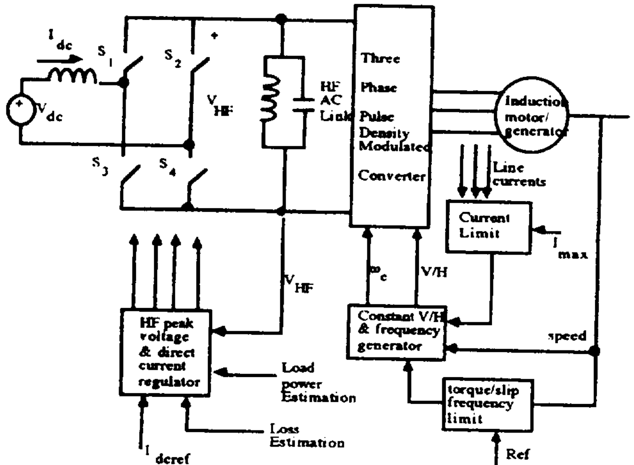


Fig. 2 Induction motor/ generator supplied from a HF link PDM converter used in ref. [8]-[9]

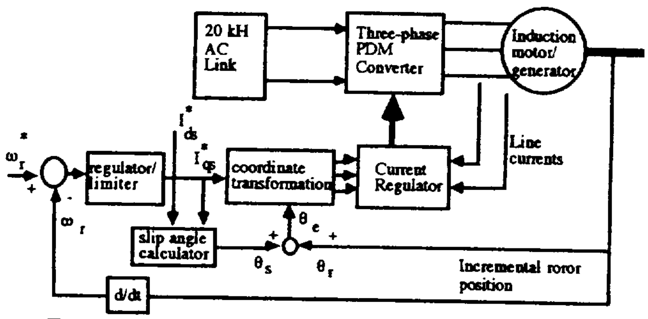


Fig. 3 FOC induction motor drive system utilizing HF link as proposed in ref. [10]-[11].

Further work by Alan and Lipo [12] investigated a 10 hp, 6000 rpm squirrel-cage dynamometer, using a high frequency (20 kHz) ac link with power fed back to the source through the converter. Speeds up to 18,000 rpm (a factor of 3:1) were achieved, using field weakening. Two squirrel-cage induction machines were interconnected via a 20 kHz parallel resonant link. One machine is operated as a generator and the other as a motor, as shown in Fig. 4. No capacitors were used to supply the reactive power to either the motor or generator. Instead, the reactive power of the entire system was supported by control of the switching converters.

Other work related to resonant link bidirectional power converters, as applied to multi-quadrant operation of induction machines without the use of capacitors, has been recently reported by Kim and Sul [13]-[14].

Although the University of Wisconsin research has demonstrated the feasibility of an isolated starter/generator induction machine unit using a high frequency link, the use of such a unit in an aircraft has yet to be investigated. A factor of 3:1 in speed for a 60 Hz system (i.e 18000 rpm), if used in a 400 Hz system, will result in speeds that demonstrate the potential for application in aircraft power systems. The use of a HF link reduces the converter losses and improves efficiency, but imposes a limit on the control system and introduces EMI problems.

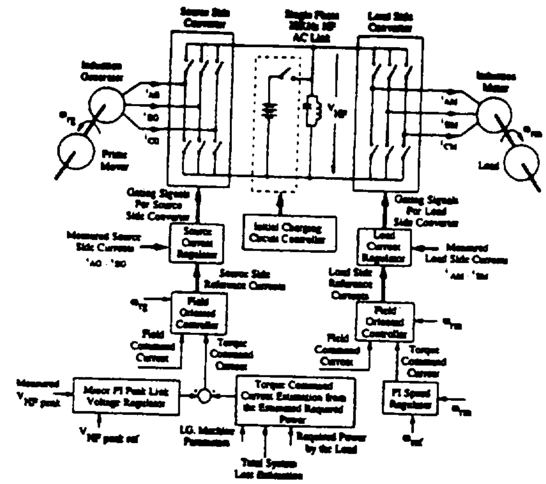
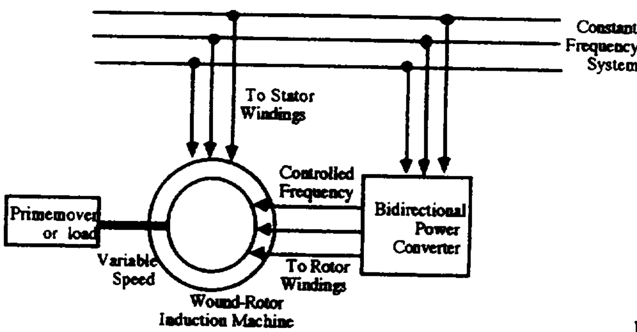


Fig. 4 Induction motor /generator isolated 3-Φ to 3-Φ power conversion reported in ref. [12]

3.2 The Doubly-Fed Brushless Machines

Brushless doubly-fed machines have been investigated as variable speed constant frequency generators for wind power generation in which the speed of the prime mover (horizontal- or vertical-axis wind turbine) is allowed to vary, but the output electrical power is maintained at a constant frequency (such as 60 Hz for the utility grid and 400 Hz for aircraft system). These generators include systems based on induction and reluctance machine technologies. Although the investigation of these machines has shown promising results for wind power generation, the application can be extended to aerospace power generation. However, one distinction that should be made is that the wind power generation is obtained at low speeds (up to 1000 rpm) [22] whereas the aerospace starter/ generators are operated at high speed, typically above 20,000 rpm [27]-[28].

Induction machines of the cage and wound-rotor types have been used as doubly-fed machines for wind power generation. The so-called slip power recovery schemes, using wound-rotor induction machines, have been a common practice known as a Scherbius-type generator [15],[19],[20],[25]-[26]. In such schemes, the power due to the rotor slip below or above synchronous speed is recovered to or supplied from the power source. The configuration of a VSCF doubly-fed wound-rotor induction machine system is shown in Fig. 5. The machine is excited at both the stator and the rotor terminals. The stator terminals are connected to the ac power supply directly, while the rotor windings are connected through a bidirectional variable frequency converter to handle the slip power in both directions. Among the three power flow ports, namely, the stator terminals, the rotor terminals and the rotor shaft, the rotor terminals act as the energy regulating port, balancing the power flow of the entire system. An important feature of slip recovery power is that the frequency of the induced electric power can be kept constant, even if the rotating speed of the induction machine changes widely. However, since the rotor is controlled by a power electronic converter, harmonic currents are fed to the rotor windings and transmitted to the power supply, thereby changing the frequency of the stator windings. One advantage of the system is its controllability by a small capacity converter. This promotes cost reduction for the doubly-fed machine in VSCF operation.



F ig. 5 **Doubly-fed wound-rotor induction machine VSCF system**

A brushless doubly-fed machine (BDFM) has a typical structure as shown in Fig. 6 [16]-[18],[21]-[22]. The fundamental feature of the system is that two sets of windings, electrically isolated and displaced by a phase angle, with different pole numbers, are equipped in the stator of the machine. One set of the three-phase stator windings, labeled as 'power windings', is excited directly from the utility supply. The other set of three-phase windings, namely, the 'control windings', acts as an equivalent set of rotor windings, and is used to regulate the energy flow through a bidirectional frequency converter. The rotor is of the cage- or reluctance-type.

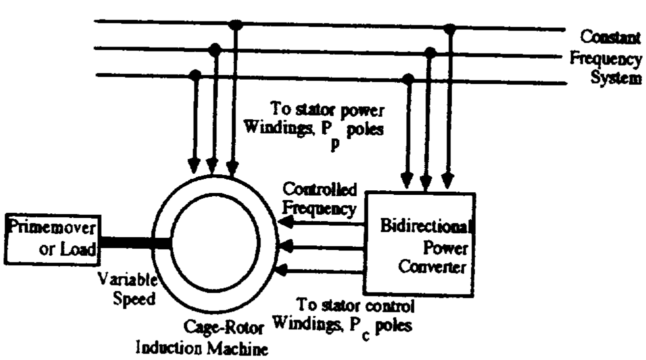


Fig. 6 Doubly-fed squirrel-cage induction machine VSCF system

A number of researchers have investigated the VSCF doubly-fed induction machines, and compared their performance to the fixed speed systems [15]-[26]. Issues studied include the effects of machine parameters on the current ripple and torque pulsation [16], and modeling of the machines using d-q transformation to improve their design and dynamic and steady-state characteristics [17],[18]. Other issues were reactive power and torque estimation, independent or decoupled control [19],[22],[24]-[26] and rotor and stator structures to achieve different doubly-fed machines [21], [23]. Reference [15] provides a qualitative comparison of the slip power recovery induction machine with the synchronous and the brushless doubly-fed induction machines. The comparison encompasses torque ripple, torsional resonance, start-up, the use of gears, reactive power control, speed range for generation, size of the machine, and the number and power rating of the devices used in the bidirectional frequency converter.

In conclusion, the potential of doubly-fed generators for VSCF wind power applications has been well investigated. A number of prototypes have been proposed, analyzed and experimentally evaluated. However, the potential use of the doubly-fed machines as starter/generators in aircraft systems has not been be studied. As was mentioned earlier, there is a significant difference between the speed range in wind power applications and that of a starter/generator in an aircraft system.

4. Switched-Reluctance Starter/Generator System

The switched reluctance machine (SRM) enjoys considerable interest for use as an integral starter/generator on future aircraft engines, as reported by researchers from Sundstrand Aerospace, GE Aircraft Engines and the University of Kentucky, through USAF Wright Laboratories [27]-[40]. Engineers envision the machine as a potential source of primary aircraft electric power and engine starter. The SRM offers a number of advantages in such applications, compared to the synchronous and induction machine technologies. The advantages are in reliability and fault tolerance. The magnetic and electric independence of the machine phases and absence of permanent magnets improve reliability. The mechanical integrity of the rotor permits high speed, high power density operation. The ability to operate in high temperature environments and at high speeds allows the possibility of direct-drive. This would allow the elimination of the gear box and hydraulic system accessories on the aircraft.

A typical switched reluctance starter/generator system used in aircraft is shown in Fig. 7. In the motoring mode, the dc bus (270 V in aircraft) delivers power to the reluctance machine through the converter, and starts the aircraft engine. In the generating mode, the dc bus delivers the excitation to the machine and the gas turbine acts as a prime mover. The power delivered by the machine exceeds the excitation power delivered by the source, and can be delivered to the dc source or pumps and other loads in the aircraft. Based on the machine phase currents and rotor position, the controller sends the appropriate signals to turn on and off the converter phases.

Initial study of the switched reluctance starter/generator system in aircraft was reported by MacMinn et al [27]-[28]. An integrated 1500 hp, 48000 rpm electric starter/generator was designed and built. The machine was operated as a motor in the constant torque and constant power modes up to a speed of 26,000 rpm and 17 hp. Then the SRM was run as a generator, delivering constant power to the dc bus over a 2:1 engine operating speed.

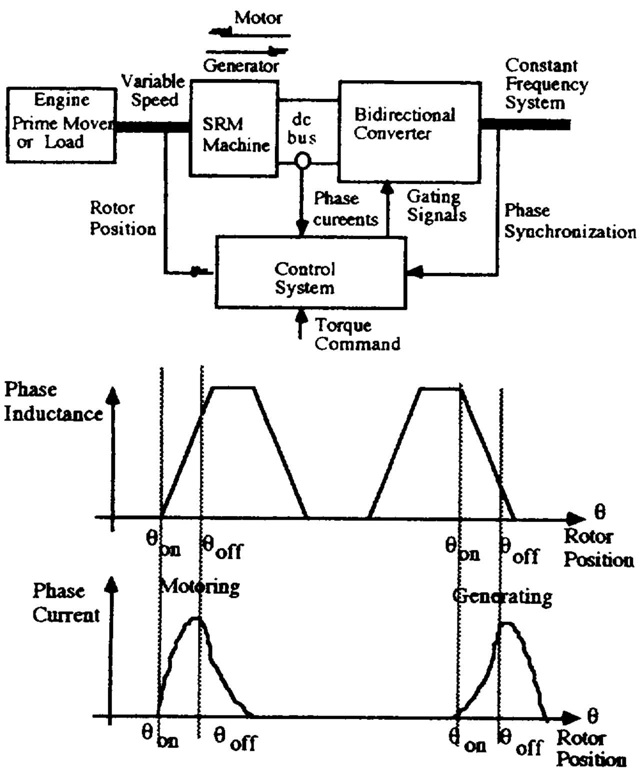


Fig. 7 Switched reluctance starter/generator system and waveforms

Many investigators have designed and built SRM starter/generator systems. Radun et al [29] described the details of a 120 hp VSCF system which operated from a 270 V dc bus to deliver power to a fuel pump. The study demonstrated a high-power density system operating over wide speed range . The use of Insulated Gate Bipolar Transistor (IGBT) and Multi-Layer Ceramic (MLC) capacitors provided increased operating temperature of the drive system.

Reference [31] described the theoretical aspects of the switched reluctance machine as a generator and its duality with the motor operation. Also discussed were the nature of the SRM generator excitation voltage and problems associated with it, together with alternate structures that remedy these problems. Additionally, the possibility of generating AC voltage with SRM generators was included. A cycloconverter capable of interfacing the SRM generator to the existing aircraft 400 Hz system was presented. The details of the cycloconverter are given in reference [35].

A series of SRM starter/generator designs and test results for gas turbine application have been reported in the past two years, highlighting the state-of-the-art developments [32]-[33], [36], [39]-40]. Issues discussed include improvement in power density , increased operating speed, power quality requirement per MIL-STD-704E, efficiency, use of power switching devices such as IGBTs and MOS-Controlled Thyristors (MCTs), parallel operation of converter for high power operation, EMI filter design, operation of the generator for different passive and active load types, converter control and elimination of the need for a position sensor. The SRM torque/speed characteristics achieved in the starter/generator studies are shown in Fig. 8. During engine starting, the machine runs as a motor and supplies a constant torque from standstill to about 13,000 rpm. Between 13,000 rpm and 26,000 rpm, the machine is run as a generator providing constant power to various engine and aircraft loads.

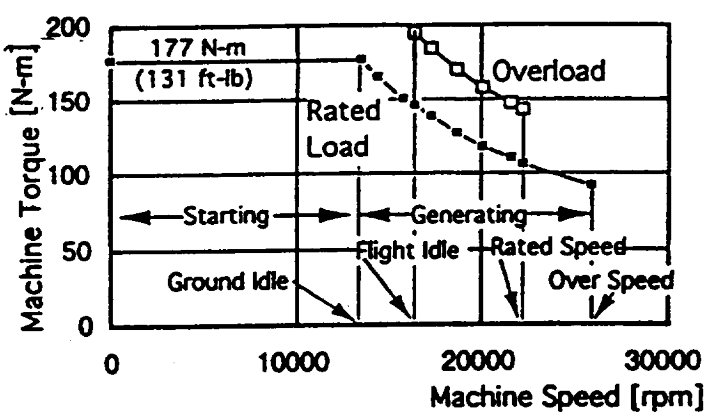


Fig. 8 State-of-the-art switched-reluctance starter/generator torque/speed characteristics reported in ref. [42]

The use of an SRM as a VSCF system for wind power generation has, also, been reported. In reference [34], a 7.5 kW SRM generator with a control scheme for VSCF application was described. A four-quadrants VSCF SRM system interfacing with a 60 Hz utility system was described in reference [43].

One major problem with the SRM starter/generator system is the dc bus voltage build-up. In reference [30], a method based on averaging, global and local linearization and model order reduction, was used to design a full-state feedback controller which regulates the steady-state load voltage, to prevent voltage build-up.

5. Advancements in Power Electronics

Continuous improvements in power electronic converters and components provide the most promising avenue for achieving the ambitious objectives of VSCF systems for aircraft power generation. Targets of power density of 1 kVA/LB and mean-time-between-failure (MTBF) of 5000 hours have been achieved, using a 60 kVA dc resonant link in a VSCF system [37].

Developments in power semiconductor devices and switching schemes, better magnetic materials, improvements in capacitor technology, and better design of motors and controllers are expected to reduce weight, size and reliability concerns of the aircraft industry in using power electronics and electric machines in VSCF technology for future aircraft power systems [37], [44]-[45].

6. Conclusions

This paper has discussed the potential candidacy of induction and reluctance machine VSCF drive technologies for an aircraft starter/generator system. A summary of reported work on the starter/generator system is included. The research on the doubly-fed induction machines has focused on VSCF for wind power generation, whereas that on switched reluctance machines has been directly studied as a VSCF technology in aircraft system. Results obtained-to-date favor the switched reluctance machine over the induction machine.

Based on the foregoing comparative review, it is recommended that the induction machine be fully investigated as a VSCF drive for aircraft systems. The findings should then be compared with the counterpart SRM system. Issues of comparison may include fault tolerance and redundancy, power density, torque requirements, overload and thermal ratings, efficiency and stability over expected operating speed range.

Acknowledgments

The authors wish to acknowledge the full funding provided by the Electrical Components and Systems Branch (EC&SB) in the Power Technology Division at NASA Lewis Research Center.

Also, the authors are grateful to David Renz and Linda Taylor of EC&SB for their helpful suggestions.

References

[1] R.E. Quigley, Jr., "More Electric Aircraft," Proceedings of 1993 Applied Power Electronics Conference (APEC'93), pp. 906-911.

[2] J.G. Vaidya, "Electrical Machines Technology for Aerospace Power Generators," Proc. of IECEC 1991, Vol. 1, pp. 7-12.

[3] J.D. Bailey, "Factors Influencing the Protection of Small-to-Medium Size Induction Generators," IEEE Trans. on Industry Applications, Vol. 24, No. 5, Sep/Oct. 1988.

[4] A.K. Al Jabri and A.I. Alolah, "Limits on The Performance of The Three-Phase Self Excited Induction Generators," IEEE Trans. on Energy Conversion, Vol. 5, No. 2, Jun. 1990, pp. 350-356.

[5] Y.H. A. Rahim, A.L. Mohamadien and A.S. Al Khalaf, "Comparison Between The Steady-State Performance of Self-Excited Reluctance and Induction Generators," IEEE Trans. on Energy Conversion, Vol. 5, No. 3, Sep. 1990, pp. 519-525.

[6] T.F. Chan, "Capacitance Requirements of Self-Excited Induction Generators," IEEE Trans. on Energy Conversion, Vol. 8, No. 2, Jun. 1993, pp. 304-311.

[7] L. Tang and R. Zavadil, "Shunt Capacitor Failures due to Windfarm Induction Generator Self-Excitation Phenomenon," IEEE Trans. on Energy Conversion, Vol. 8, No. 3, Jun. 1993, pp. 513-519.

[8] P.K. Sood and T.A. Lipo, "Power Conversion Distribution System Using a Resonant High Frequency AC Link," IEEE Trans. on Industry Applications, Vol. 24, No. 2, Mar/Apr. 1988, pp. 586-596.

[9] P.K. Sood and T.A. Lipo and I.G. Hansen, "A Versatile Power Conversion for High Frequency Link," IEEE Trans. on Power Electronics, Vol. 3, No. 4, Oct. 1988, pp. 383-390.

[10] S.K. Sul and T.A. Lipo, "Field-Oriented Control of an Induction Machine in a High Frequency Link Power System," IEEE Trans. on Power electronics, Vol. 5, No. 4, Oct. 1990.

[11] S.K. Sul and T.A. Lipo, "Design and Performance of a High Frequency Link Induction Motor Drive operating at Unity Power Factor," Proceedings of IEEE-IAS Annual Meeting, October 1988, pp. 308-313.

[12] I. Alan and T.A. Lipo, "Control of a Poly-phase Induction Generator/Induction Motor Conversion System Completely Isolated from the Utility," IEEE Trans. on Industry Applications, Vol. 30, No. 3, May/Jun. 1994.

[13] J.W. Choi and S.K. Sul, "Resonant link Bidirectional Power Converter: Part I- Resonant Circuit," IEEE Trans. on Power Electronics, Vol. 10, No. 4, July 1995, pp. 479-484.

[14] J.W. Choi and S.K. Sul, "Resonant link Bidirectional Power Converter: Part II- Application to Bidirectional AC Motor Drive Without Electrolytic Capacitor," IEEE Trans. on Power Electronics, Vol. 10, No. 4, July 1995, pp. 485-493.

[15] H.L. Nara and B. Dube', " Slip Power Recovery Induction Generators For Large Vertical Axis Wind Turbine," IEEE Trans. on Energy Conversion, Vol. 3, No. 4, Dec. 1988, pp. 733-737.

[16] A.K. Wallace and R. Spee, "The Effects of Motor Parameters on the Performance of Brushless DC Drives," IEEE Trans. on Power Electronics, Vol. 5, No. 1, Jan. 1990, pp. 2-8.

[17] L. Xu, F. Liang and T.A. Lipo, "transient Model of A doubly-Excited Reluctance Motor," IEEE Trans. on Energy Conversion, Vol. 6, No. 1, March 1991, pp. 126-133.

[18] R. Li, A. Wallace, R. Spee and Y. Wang, "Two-Axis Model Development of Cage-Rotor Brushless Doubly-Fed Machines," IEEE Trans. on Energy Conversion, Vol. 6, No. 3, Sep. 1991, pp. 453-460.

[19] M. Yamamoto and O. Motoyoshi, "Active and Reactive Power Control for Doubly-Fed Wound Rotor Induction Generator," IEEE Trans. on Power Electronics, Vol. 6, No. 4, Oct. 1991, pp. 624-629.

[20] K. Shibata and K. Taka, "A self-Cascaded Induction Generator Combined with a Separately Controlled Inverter and a Synchronous Condenser," IEEE Trans. on Industry applications, Vol. 28, No. 4, July/Aug. 1992, pp. 797-807.

[21] L. Xu, Y. Tang and L. Ye, "Comparison Study of Rotor Structures of Doubly Excited Brushless Reluctance Machine by Finite Element Analysis," IEEE Trans. on Energy Conversion, Vol. 9, No. 1, March 1994, pp. 165-171.

[22] C.S. Brune, R. Spee and A.K. Wallace, "Experimental Evaluation of a Variable-Speed, Doubly-Fed Wind-Power Generation System," IEEE Trans. on Industry Applications, Vol. 30, No. 3, May/Jun. 1994, pp. 648-655.

[23] L. Xu and L. Ye, "Analysis of a Novel Stator Winding Structure Minimizing Harmonic Current and Torque Ripple for Dual Six-Step Converter-Fed High Power Ac Machines," IEEE Trans. on Industry Applications, Vol. 31, No. 1, Jan./Feb. 1995, pp. 84-90.

[24] R. Li, A. Wallace and R. Spee, "Determination of Converter Control Algorithms for Brushless Doubly-Fed Induction Motor Drives Using Floquet and Lyapunov Techniques," IEEE Trans. on Power Electronics, Vol. 10, No. 1, Jan. 1995, pp. 78-85.

[25] L. Xu and W. Cheng, "Torque and Reactive Power Control of a Doubly Fed Induction Machine by Position Sensorless Scheme," IEEE Trans. on Industry Applications, Vol. 31, No. 3, May/Jun. 1995, pp. 636-642.

[26] Y. Tang and L. Xu, "A Flexible Active and Reactive Power Control Strategy for a Variable Speed Constant Frequency Generating System," IEEE Trans. on Power Electronics, Vol. 10, No. 4, July 1995, pp. 472-478.

[27] S.R. MacMinn and W.D. Jones, "A Very High Speed Switched-Reluctance Starter Generator for Aircraft Engine Applications," Proceedings of NAECON'89, May 22-26, 1989, Dayton, OH, pp. 1758-1764.

[28] S.R. MacMinn and J.W.Sember, "Control of A Switched-reluctance Aircraft Engine Starter-Generator Over A Very wide Speed range" Proceedings of IECEC, Aug. 6-11,1989, pp. 631-638.

[29] A.V. Radun, "High Power Density Switched Reluctance Motor Drive for Aerospace Applications," IEEE Trans. on Industry Applications, Vol.. 28, No. 1, Jan./Feb. 1992, pp. 113-119.

[30] D.E. Cameron & J.H. Lang, "The Control of High-Speed Variable Reluctance Generators in Electric Power Systems," IEEE Trans. on Industry Applications, Vol. 29, No. 6, Nov./Dec. 1993.

[31] A.V. Radun, "Generating with the Switched Reluctance Motor," Proc. of The 1994 Applied Power Electronics Conference (APEC'94), Feb. 13-17, pp. 41-47.

[32] A.R. Radun, J.P. Lyons, J.Ruison, P. Sanza and E. Richter, "Engine Starter/Generator System Testing," Aerospace Engineering, July 1994, pp. 23-26.

[33] E. Richter, J.P. Lyons, C. Ferreira, A.R. Radun and E. Ruchstadter, " Starter/ Generator Preliminary Testing of a 250-kW reveals Favorable Results," Aerospace Engineering, Oct. 1994, pp. 7-10.

[34] R. Cardenas, W.F. Ray, G.M. Asher, "Switched-Reluctance Generators for Wind Energy Applications," Proc. of IEEE 1995 Applied Power Electronics Conf. (APEC'95), pp. 559-564.

[35] A. Radun and H. Jiang, "400 Hz AC Generator/ Cycloconverter using Switched Reluctance Technology for Aircraft Retrofit/Upgrade Applications," WPAF contract report, April 1995.

[36] C.A. Ferreira, S.R. Jones, W.S. Heglund and W.D. Jones, "Detailed design of a 30-kW switched reluctance starter/generator system for gas turbine engine application," IEEE Trans. on Industry Applications, Vol. 31, No. 3, May/Jun. 1995, pp. 553-561.

[37] T.M. Jahns and M.A. Maldonado, "A new resonant link aircraft power generating system," IEEE Trans. on Aerospace and Electronics Systems, Vol. 29, pp. 206-214, Jan. 1993.

[38] T.M. Jahns, R.W. De Doncker, AV. Radun. P.M. Szczesny and F.G. Turnbull, "System design considerations for a high-power aerospace resonant link converter," IEEE Trans. on Power Electronics, Vol. 8, No. 4, Oct. 1993, pp. 663-672.

[39] C.A. Ferreira, S.R. Jones and W.S. Heglund, "Performance Evaluation of a Switched Reluctance Starter/Generator System under Constant Power and Capacitive Type Loads," IEEE Trans. on Industry Applications, Vol. 31, No. 3, May/Jun. 1995, pp. 553-561.

[40] W.S. Heglund, B. T. Drager, S.R. Jones and C.A. Ferreira "Design and implementation of a five-hp, switched reluctance, fuel-lube, pump motor drive for gas turbine engine," IEEE Trans. on Power Electronics, Vol. 10, No. 1, Jan. 1995, pp. 55-61.

[41] S.R. Jones and B.T. Drager, "Performance Evaluation of a High-Speed Switched Reluctance Starter/Generator System using Electronic Position Sensing," Proc. of the 1995 IEEE IAS Annual Meeting, pp. 249-253.

[42] E. Richer and C. Ferreira, "Performance Evaluation of a 250 kW Switched Reluctance Starter Generator," Proc. of the 1995 IEEE IAS Annual Meeting, pp. 434-440.

[43] G.Rim and R. Krishnan, "Variable Speed Constant Frequency Power Conversion with A Switched Reluctance Machine," Proc. of IEEE 1994 Applied Power Electronics Conf. (APEC'94), pp. 63-71

[44] M. Elbuluk and M.D. Kankam, "Motor Drive Technologies for the Power-By-Wire Program Part I: Motors and Controllers," IEEE Aerospace and Electronics Magazine, Nov. 1995, pp. 37-42.

[45] M. Elbuluk and M.D. Kankam, "Motor Drive Technologies for the Power-By-Wire Program Part II: Power Electronic Converters and Devices," IEEE Aerospace and Electronics Magazine, Dec. 1995, pp. 31-36.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1996	Technical Memorandum

4. TITLE AND SUBTITLE
Potential Starter/Generator Technologies for Future Aerospace Applications

5. FUNDING NUMBERS
WU-233-02-03-06

6. AUTHOR(S)
Malik E. Elbuluk and M. David Kankam

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-10257

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-107224

11. SUPPLEMENTARY NOTES
Prepared for the National Aerospace and Electronics Conference cosponsored by IEEE, WBAFB, and AESS, Dayton, Ohio, May 20-24, 1996. Malik E. Elbuluk, University of Akron, Department of Electrical Engineering, Akron, Ohio 44325-3904, and Summer Faculty Fellow at Lewis Research Center; M. David Kankam, NASA Lewis Research Center. Responsible person, M. David Kankam, organization code 5430, (216) 433-6143.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories 07 and 08

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This paper presents a search and comparative review* of the literature available on variable speed constant frequency (VSCF) technologies. In particular, most of the progress made in the past ten years, using power electronics and electric machines for VSCF systems, is reported. Two VSCF systems, based on induction and switched reluctance machine technologies, are presented. The research on the singly-and doubly-fed induction machines has focused on VSCF for wind power generation, whereas that on switched reluctance machines has been directly studied as a VSCF technology in aircraft system. Results obtained so far favor the switched reluctance machine over the induction machine. Based on the foregoing comparative review, it is recommended that the induction machine be fully investigated as a VSCF drive for aircraft systems. The findings should then be compared with the counterpart SRM system. Issues of comparison may include fault tolerance and redundancy, power density, torque requirements, overload ratings, temperature range and cooling, efficiency and stability over expected operating speed range.

14. SUBJECT TERMS
Aerospace; Aircraft system; Aircraft engines; Starter/Generators; Induction machines; Switched reluctance machines; Brushless machines; Motor drives; Variable speed constant frequency

15. NUMBER OF PAGES
10

16. PRICE CODE
A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

National Aeronautics and
Space Administration
Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135-3191